Final Technical Report

CENTRAL U.S. SHEAR WAVE VELOCITY DATABASE WITH ACCOMPANYING GEOLOGICAL/GEOTECHNICAL INFORMATION OF NONLITHIFIED GEOLOGIC MATERIALS

External Grant Award Number 04-HQ-GR-0074

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Abstract

The project collected shear wave velocity measurements of nonlithified geologic materials along with lithologic descriptions and any geotechnical properties for the cooperative earthquake hazard mapping areas in St. Louis Urban Hazard Mapping and the Tri-State (Evansville) Urban Hazard Mapping area of Indiana, Kentucky and Illinois. The geology and shear wave velocity information were gathered through boreholes and seismic profiles. This will ultimately produce a region-specific relationship between lithologies and seismic wave velocities for use in production of soil profile type derivative maps. This project also measured in situ shear wave velocities in materials and areas where no or few values existed, and collected lithologic data at these new shear wave velocity sites.

Introduction

The project collected shear wave velocity measurements of nonlithified geologic materials along with lithologic descriptions and geotechnical properties for the cooperative earthquake hazard mapping in the greater St. Louis and the Tri-State (Evansville) areas of Indiana, Kentucky and Illinois. Funding on this project was restricted to only collecting the data and not placing it into a database. This data will be used to produce a region-specific relationship between lithologies and seismic wave velocities for use in production of soil profile type derivative maps in the future.

The CUSEC project personnel also coordinated with the U.S. Geological Survey's cone penetrometer testing (CPT) program in the Central U.S. to help select sites for testing. The USGS's CPT rig was able to supply soil descriptions produced by the CPT relationships and also downhole shear wave velocity measurements.

Investigations undertaken

<u>Illinois Geological Survey</u>

Horseshoe Lake – Monks Mound Quad Within the last few years, the Illinois State Geological Survey drilled two boreholes down to bedrock in Horseshoe Lake State Park under another funded project. Horseshoe Lake State Park is in the Monks Mound quadrangle which is part of the St. Louis Urban Hazard Mapping project. This area is part of the Mississippi River "floodplain" and consists of several thick layers of sands and gravels (tables 1 & 2) totaling about 108 feet. This setting represents large portions of the Monks Mound, Granite City and Cahokia Quadrangles which have been selected by the St. Louis Urban Hazard Mapping Project team as pilot study areas. These boreholes were cased in PVC so that downhole geophysical measurements could be made. Downhole shear wave velocity measurements were made in 2004 in the two boreholes for this CUSEC project. Figure 1 & 2 shows the downhole shear wave measurements for these holes. The lower 45 to 50 feet of these sands and gravels belongs to the Henry Formation of outwash materials from the melting glaciers. The sands and gravels over the Henry Formation are part of the Cahokia Formation. They both have very similar shear wave velocity profiles except for an area near the boundary between the Henry and Cahokia formations in borehole HSL-2, where several feet of fine, dense sand have a higher velocity.

Lebanon – Lebanon Quad This location is in the greater St. Louis metro area and was a hole of opportunity to collect some more downhole shear wave velocity values. This work was performed just north of Lebanon, Illinois where a valley cut into the bedrock that crosses the area. This 182 foot deep borehole was drilled by the ISGS under another project (table 2). Downhole shear wave velocity measurements were performed in the borehole under this CUSEC project (figure 3). Also a 1-mile long shear wave reflection survey was performed.

Table 1. Borehole summary for HSL4 in Horseshoe Lake State Park, Illinois

Top Depth (ft)	Bottom Depth (ft)	Material Description	Formation Name
0	11.2	Silt and clay	
11.2	55.0	Sand w/ a few pebbles	Cahokia
55.0	108.5	Sand w/ some pebbles	Henry
108.5		Limestone bedrock	Mississippian

Table 2. Borehole summary for HSL2 in Horseshoe Lake State Park, Illinois.

Top Depth (ft)	Bottom Depth (ft)	Material Description	Formation Name
0	10.2	Silt and clay	
10.2	52.8	Sand w/ a few pebbles	Cahokia
52.8	67.2	Very fine sand	Cahokia
67.2	108.8	Sand w/ some pebbles	Henry
108.8		Limestone bedrock	Mississippian

Table 3. Borehole summary for borehole near Lebanon, Illinois.

Top Depth (ft)	Bottom Depth (ft)	Material Description	Formation Name
0	8	Silt, loess	Peoria Silt
8	15	Silt, loess	Roxana Silt
15	45.8	Pebbly silt loam to diamicton	Glasford
45.8	165.3	Diamicton	Banner
165.3	174.1	Silty to sandy loam, alluvium	Banner, Canteen Mbr A
174.1	179.4	Conglomerate, alluvium	Banner, Canteen Mbr B
179.4	181.1	Shale bedrock	Pennsylvanian

Depth (m)	S-Vel. (m/s)
1.6764	47
2.8956	112
4.1148	174
5.334	198
6.5532	211
7.7724	209
8.9916	213
10.2108	227
11.43	216
12.6492	222
13.8684	247
15.0876	235
16.3068	239
17.526	252
18.7452	242
19.9644	245
21.1836	251
22.4028	248
23.622	239
24.8412	236
26.0604	249
27.2796	253
28.4988	262
29.718	275
30.9372	307

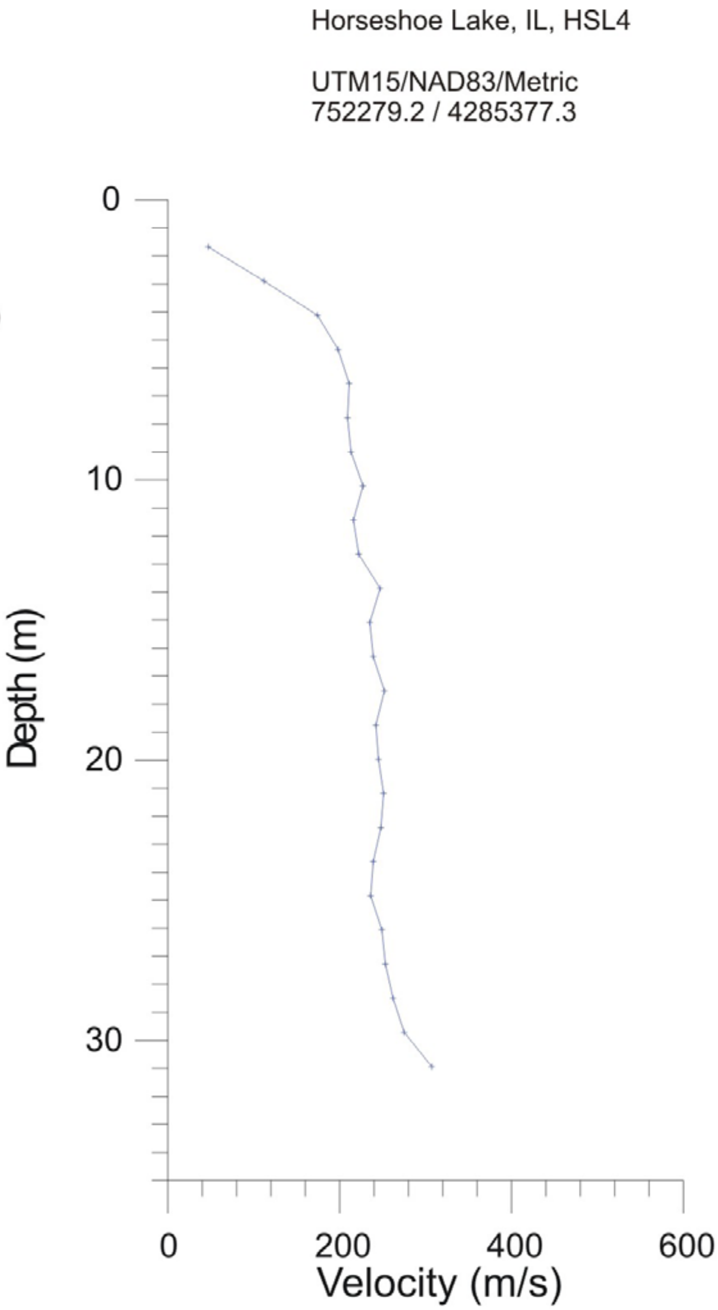

Figure 1. Downhole shear wave velocity measurements in borehole HSL4 in Horseshoe Lake State Park, Illinois.

Depth (m)	S-Vel. (m/s)
1.8288	75
3.048	98
4.2672	104
5.4864	131
6.7056	178
7.9248	203
9.144	202
10.3632	220
11.5824	272
12.8016	297
14.0208	273
15.24	274
16.4592	338
17.6784	425
18.8976	371
20.1168	287
21.336	252
22.5552	256
23.7744	281
24.9936	288
26.2128	278
27.432	286
28.6512	328
29.8704	378
31.0896	378

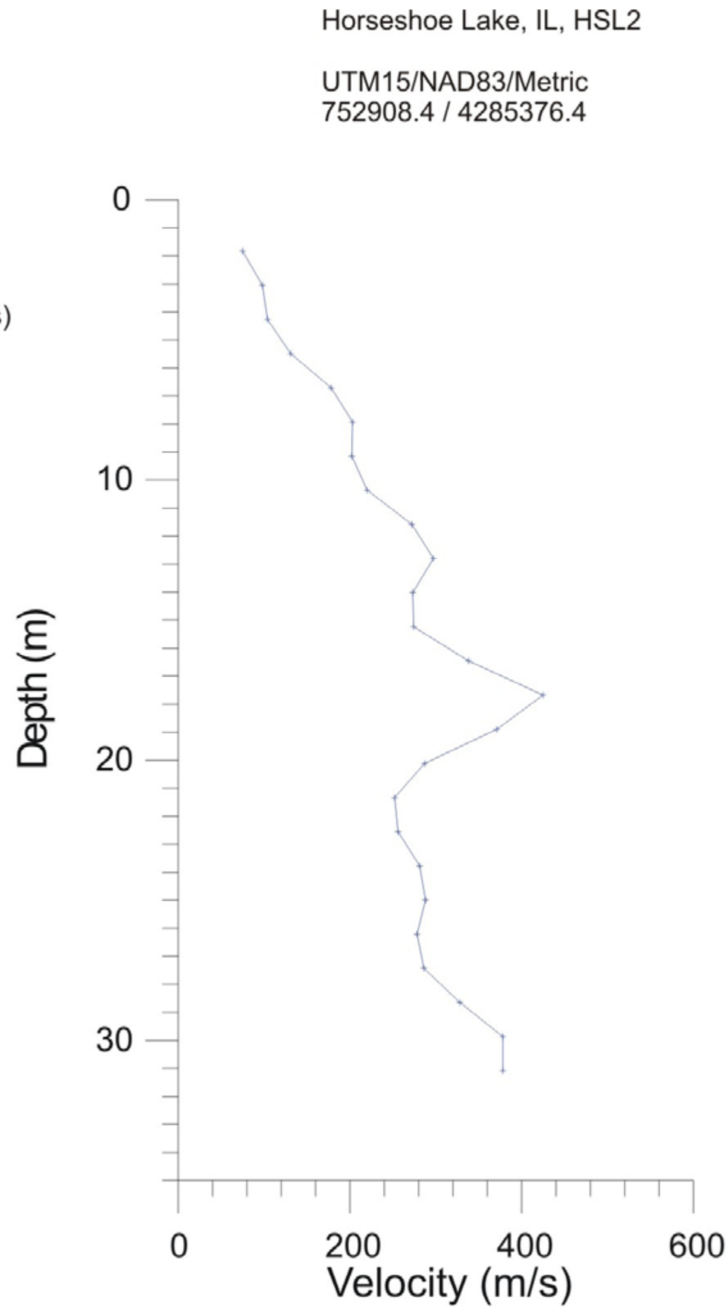

Figure 2. Downhole shear wave velocity measurements in borehole HSL2 in Horseshoe Lake State Park, Illinois.

Depth (m)	S-Vel. (m/s)
1.8288	133
3.048	223
4.2672	227
5.4864	281
6.7056	244
7.9248	172
9.144	153
10.3632	175
11.5824	270
12.8016	401
14.0208	484
15.24	504
16.4592	433
17.6784	496
18.8976	580
20.1168	524
21.336	550
22.5552	574
23.7744	555
24.9936	713
26.2128	691
27.432	423
28.6512	320
29.8704	244
31.0896	233
32.3088	333
33.528	444
34.7472	450
35.9664	485
37.1856	401
38.4048	373
39.624	538
40.8432	729
42.0624	693
43.2816	606
44.5008	529
45.72	528
46.9392	466
48.1584	408
49.3776	420
50.5968	452
51.816	458
53.0352	481

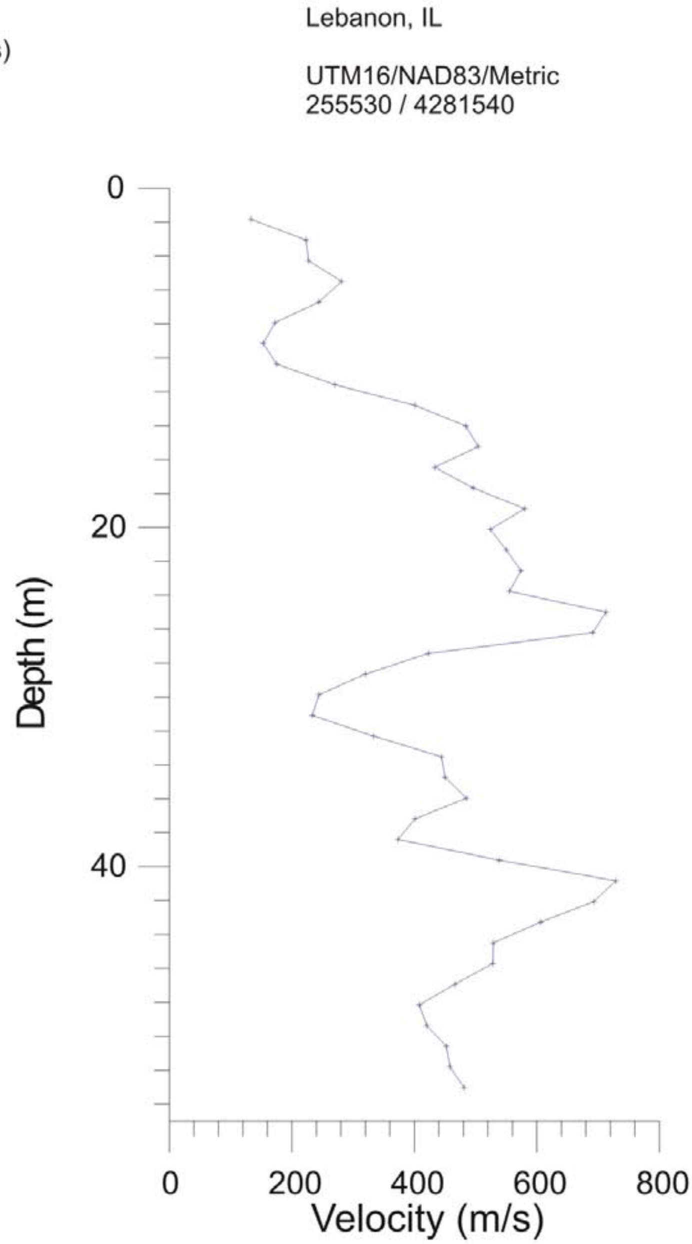

Figure 3. Downhole shear wave velocity measurements in borehole near Lebanon, Illinois.

Coordination with USGS SCPT

We coordinated with Tom Holzer and Tom Noce of USGS on performing shear wave & cone penetrometer testing at 5 sites along the Wabash Valley Seismic Zone. Sites were selected and utility clearance was performed near the large paleoliquefaction sites on the Wabash River just north and south of Vincennes; Maunie, Illinois; the seismic station in New Harmony, Indiana and the Mulzer sand and gravel quarry near Griffin, Indiana (figure 4). Test results are shown in figures 5-7.

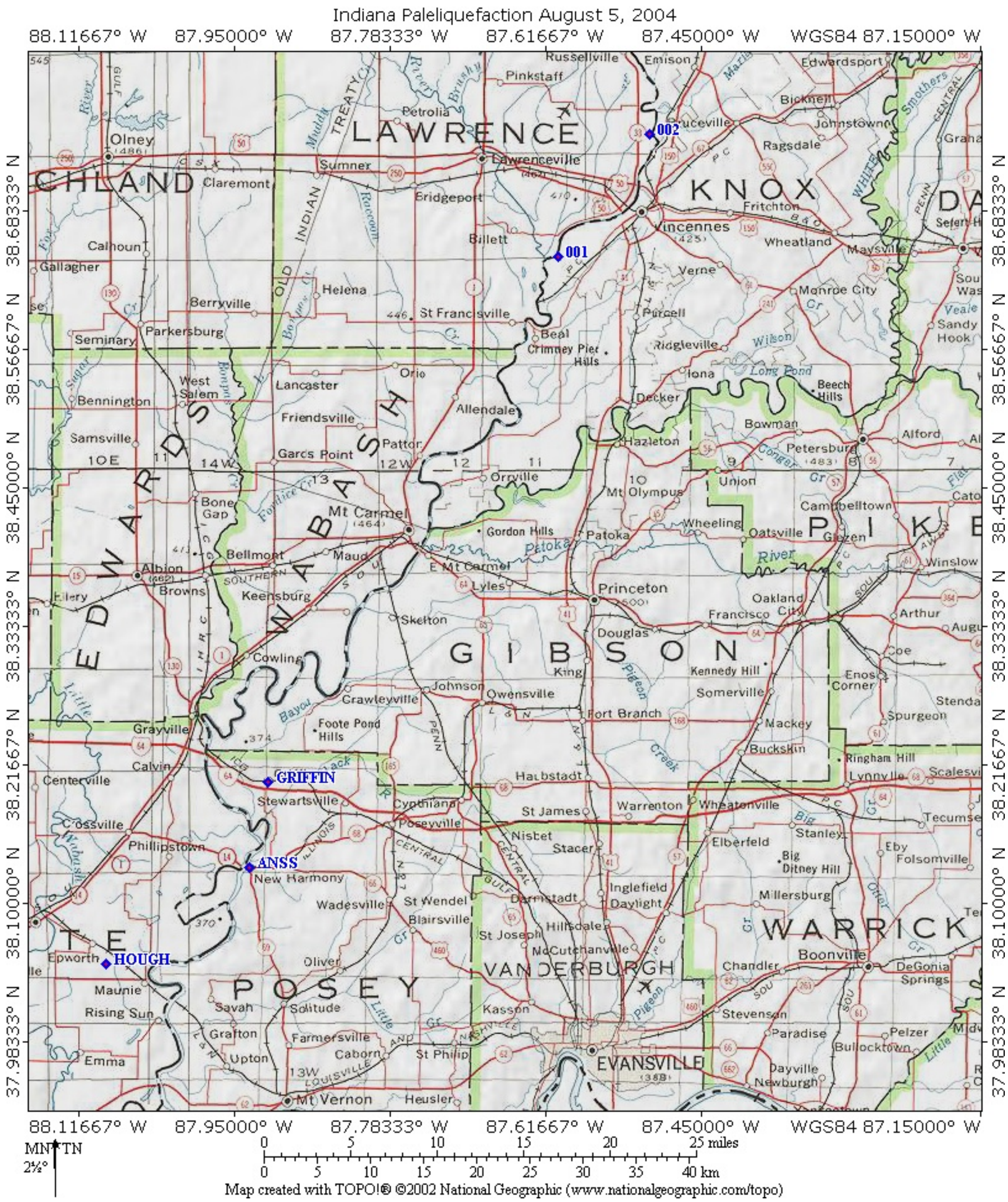

Figure 4. Location of USGS SCPT test locations in the Wabash River Valley.

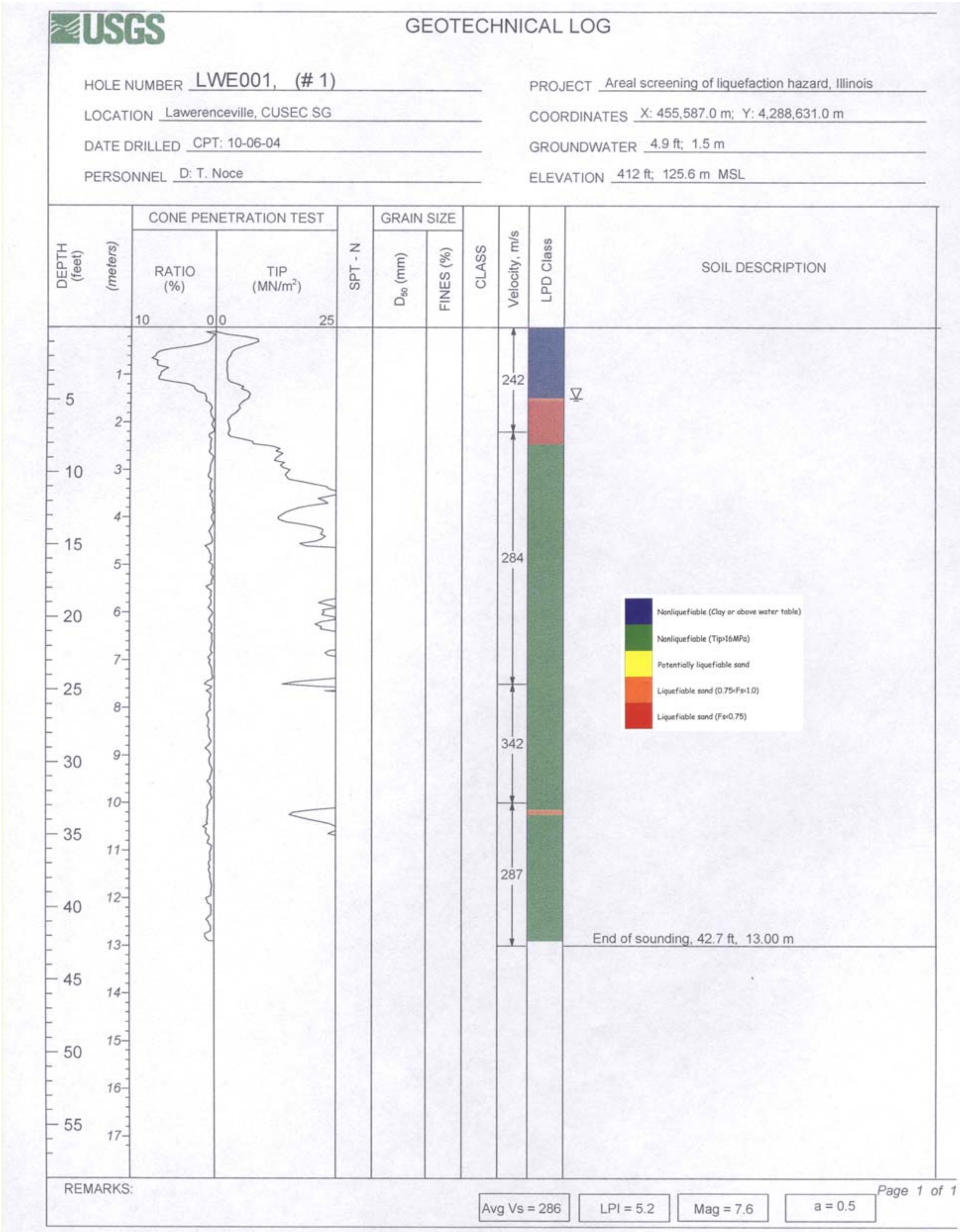

Figure 5. USGS CPT, liquefaction potential classification and shear wave velocities Lawrence County, Illinois (002 site – figure 4).

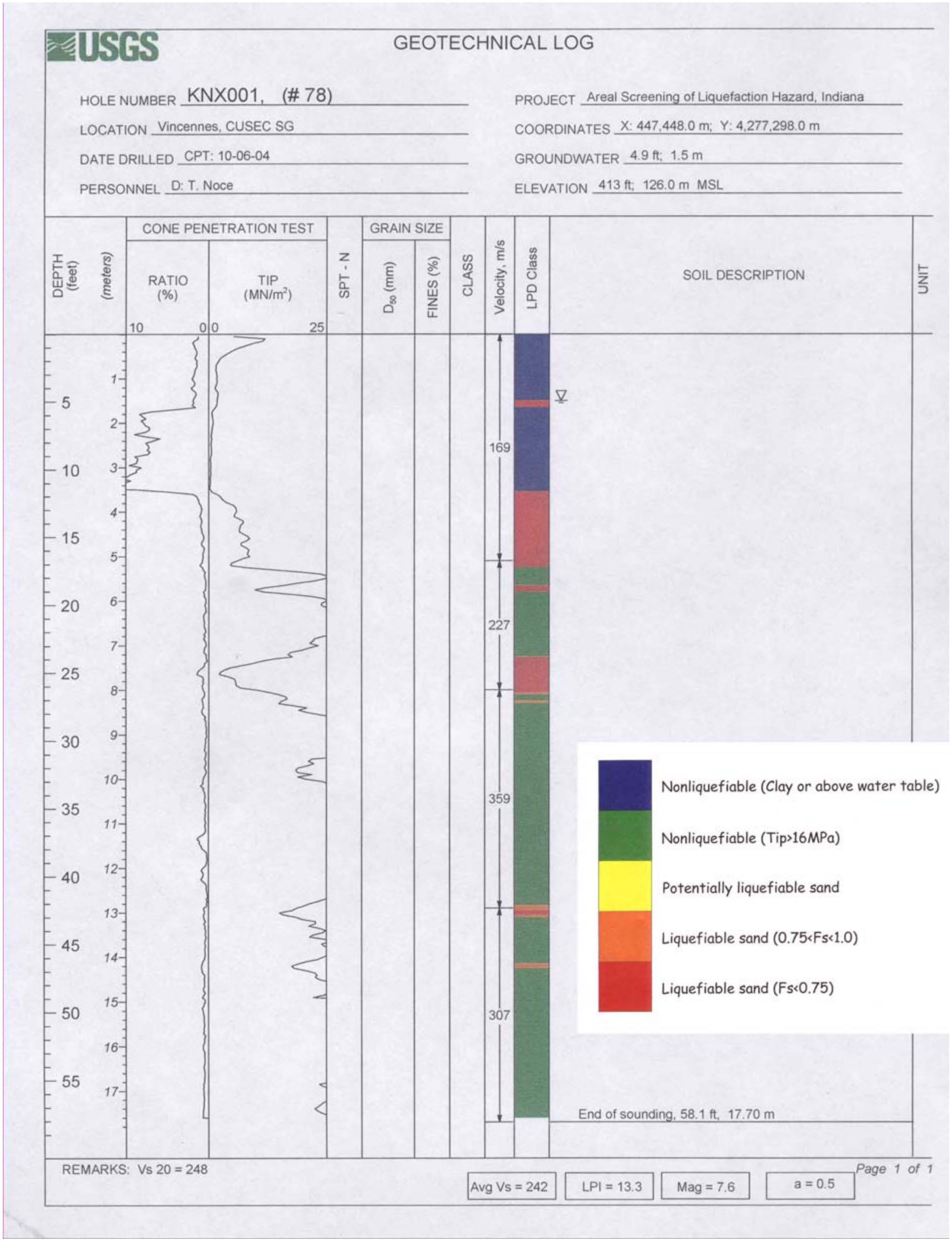

Figure 6. USGS CPT, liquefaction potential classification and shear wave velocities Knox County, Indiana (001 site – figure 4).

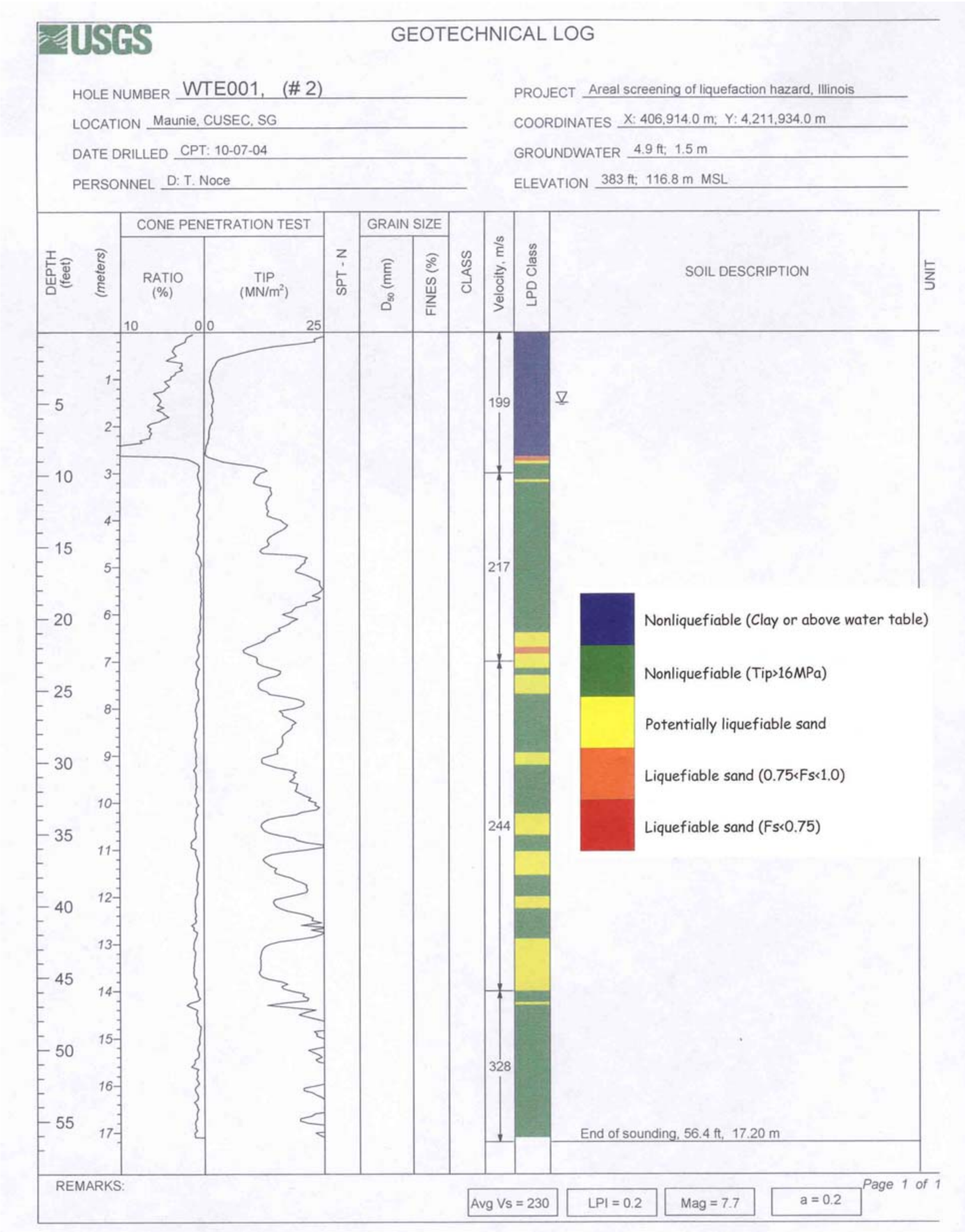

Figure 7. USGS CPT, liquefaction potential classification and shear wave velocities White County, Illinois (Hough site – figure 4).

Indiana Geological Survey

Introduction. The Indiana Geological Survey (IGS) in cooperation with the Illinois State Geological Survey (ISGS) is conducting an evaluation of high-resolution seismic-reflection data (HRSRD) in a portion of the Bluegrass Creek and Pigeon Creek drainage basin as part of a seismic risk investigation in the greater Evansville area, Indiana. The goal of this project is to generate the information essential to adequately define the three-dimensional distribution and thickness of seismically sensitive sediments such as wet sands and thick, soft clays. Such information is essential to evaluate tributary valley-fill models, and to provide the data needed to map lithologies and associated liquefaction and shaking susceptibilities here and in similar tributary basins of the Ohio, Wabash, and Mississippi rivers

In the fall of 2004, approximately 4.5-miles of seismic lines were acquired in three segments, County Line Road north of Pigeon Creek, Burkhardt Road south of Pigeon Creek, and Kimber Lane north of Highway 66. In addition, a single continuously cored test was drilled to bedrock (depth of 85 feet) along the County Line Road seismic line.

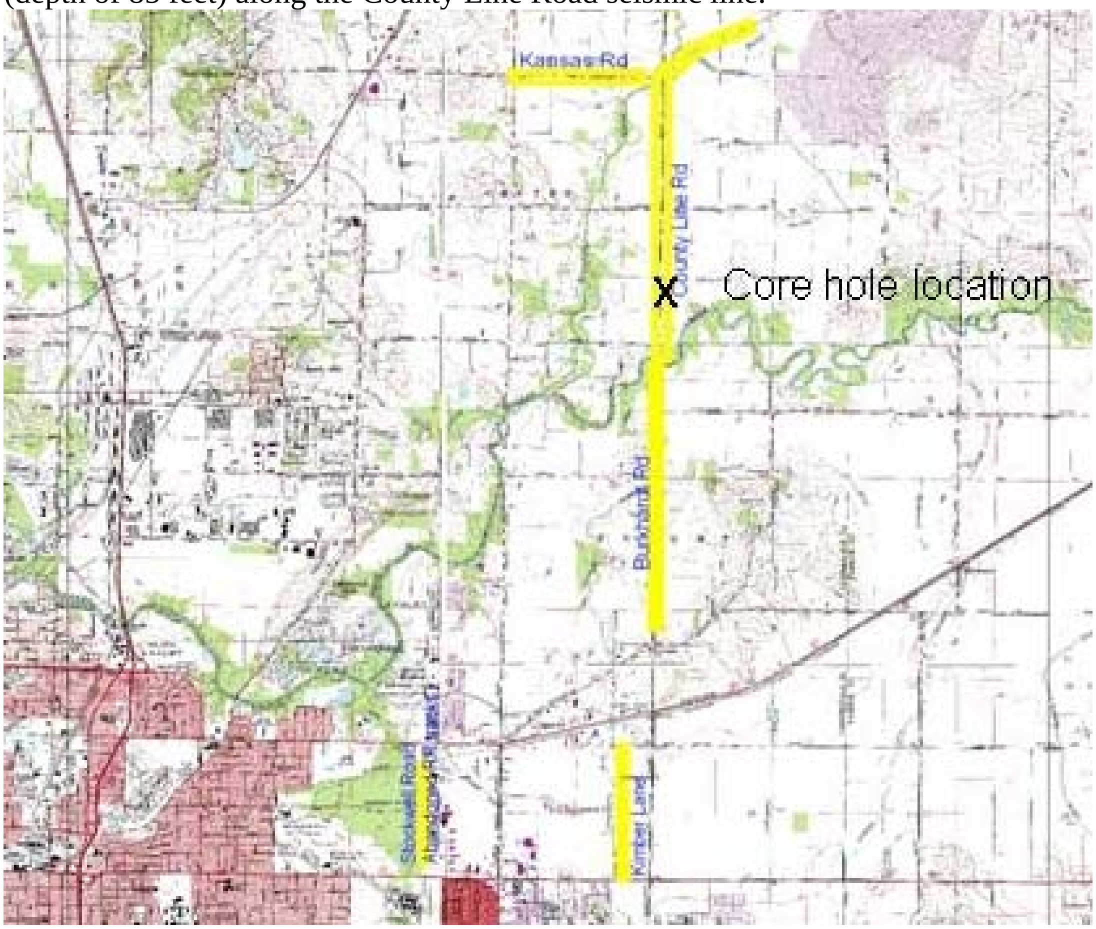

Figure 8. Map showing location of seismic lines and corehole drilled as part of the joint Indiana Geological Survey and the Illinois State Geological Survey investigation into the nature of the paleo-valley-fill of the Pigeon and Bluegrass creek tributary network. Seismic lines were not run along either Kansas Road or Stockwell Road.

These north-south oriented lines link areas where vertical two-dimensional sedimentary packages had been previously identified by the IGS utilizing extant downhole geophysical log profiles. The HRSRD lines were also selected to intersect recently acquired U.S. Geological Survey Seismic Cone Penetrometer Tests (CPT) (Figure 9).

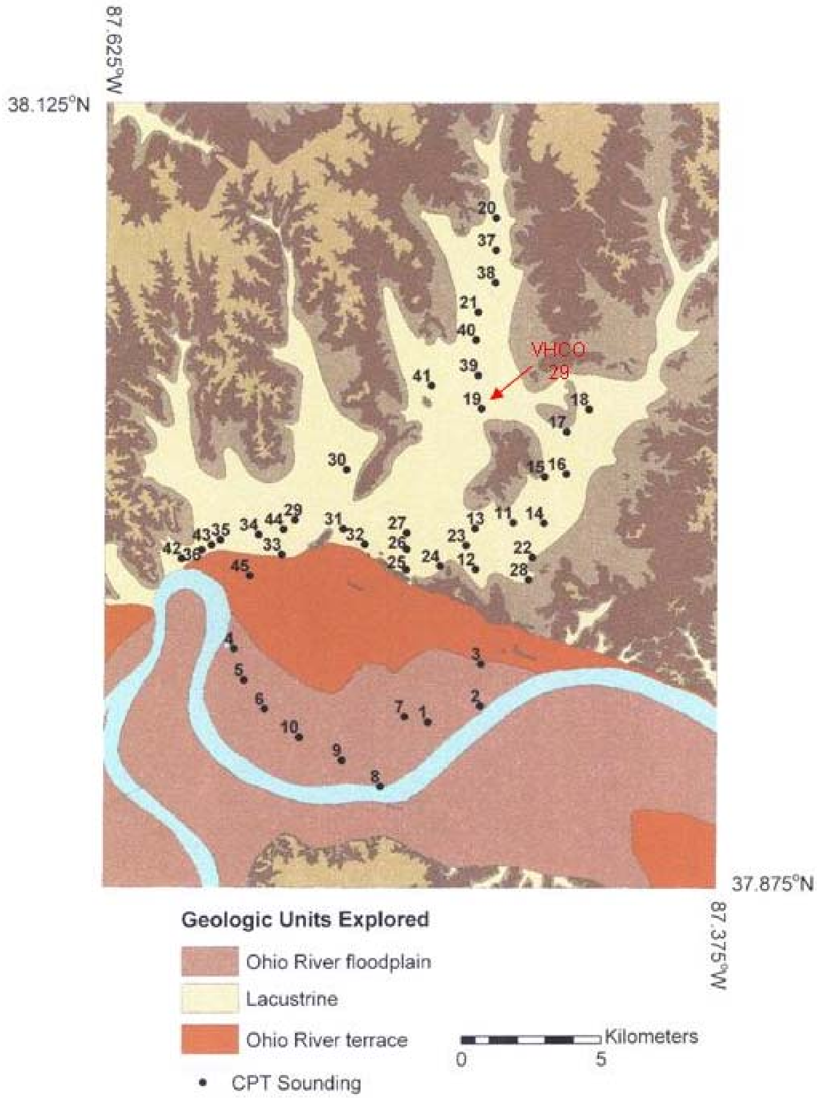

Figure 9. Location map of USGS CPT soundings in the Evansville, Indiana area. Geology provided by the Indiana Geological Survey. Map was modified from the 2004 USGS FY03 Final Report to the Nuclear Regulatory Commission. CPT sounding VHCO 29 has been correlated to the recently acquired subsurface data reported herein (see figures 10 and 11).

The borehole was slow gamma-ray logged and was subjected to downhole shear wave velocity measurements. The gamma-ray log was then compared to the preexisting nearby CPT sounding and to the seismic data (figure 10).

Study Results

The recently acquired seismic data, coupled with the core and nearby CPT data indicated that the Quaternary from Kimber Lane north to County Line Road can be subdivided into a lower unit and an upper unit. A laterally continuous, horizontal reflector separates the two units (figures 10, 11 and 13). The reflector marks the base of the upper interval which consists of calcareous thinly interlayered facies ranging from loam to silty clay to clay. The upper unit preserves multiple 2-3 ft cycles reflecting fluctuations between very shallow lake facies and exposed, unrooted, but bioturbated mudflat facies. The bioturbation in this interval appears to be *Ediaphichnium*, pelleted-fills of earthworms burrows. Earthworms typically live in alluvial, palustrine and marginal-lacustrine environments and are air-breathers so they must live above the water table but have enough moisture to keep their bodies from drying out (Hasiotis, S., 2002). The lake facies are unbioturbated and well-laminated. Both facies preserve ostracods.

Immediately below the seismic reflector boundary is the lower unit consisting in the upper most part of a series of stacked gleyed soil sequences that include rootlets, mottles, and well-developed clay skins (figure 10). This overlies a medium to fine-grained sand that is massive to ripple and horizontally laminated. This sand is interpreted as a marginal channel sand, perhaps a splay associated with a thicker channel facies present just to the north. This channel can be identified by the wedge-shaped geometry of the seismic reflectors that enclose some steeply inclined reflectors that are interpreted to be the accretionary surfaces of a migrated fluvial point bar (figure 11). Below this fluvial facies are cyclic facies that consist of pebbly coarse-grained sands that grade upwards and downwards into fine-grain sand to loam to silty clay to clay. These cycles are interpreted to reflect lake level fluctuations. The lacustrine facies are well-laminated and unbioturbated. The coarser units typically show evidence of subaerial exposure and weak pedogenic development including sparse rootlets, noncalcareous and gleyed horizons. The coarser facies all contain abundant coal fragments, weathered shale fragments and sands derived from the local Pennyslvanian deposits. This is in stark contrast to the upper unit which generally lacks indicators of local bedrock input into the sediment load. Some of the coarser pebbly units can be classified as diamictons. We interpret the interval to be a series of stacked debris flows into a tributary lake. The flows originated along the nearby valley walls during mass wasting.

Although the IGS map for this area indicates lacustrine facies dominate the Pigeon and Bluegrass Creek drainages, most of the facies in the upper unit suggest very shallow water conditions and incipient pedogenesis. The thickest lake deposit occurs near the base of the lower unit and consists of 5 feet of laminated, grey clay (figure 10). Seismic reflectors in the lower unit indicate that the facies on-lap the Quaternary-Pennsylvanian unconformity (figure 13). The fact that the reflectors don’t mantle the unconformity supports the interpretation that the paleovalley filled incrementally from a series of stacked lacustrine, marginal lacustrine and fluvial sequences over a broad area rather than during a single fill episode from a deep lake.

The best developed soils occur at the very top of both units. The paleosol at the top of the lower unit suggests a major sequence boundary that may reflect a significant time break between the two units. The investigation will attempt to date this boundary and the lower units in the near future.

Initial comparison shows a generally favorable correlation of IGS gamma-ray log response to the

USGS CPT log VHCO29 friction ratio log (figure 10). Multiple cycles in the upper unit can be directly correlated to both logs. This phase of the study will be expanded in the near future.

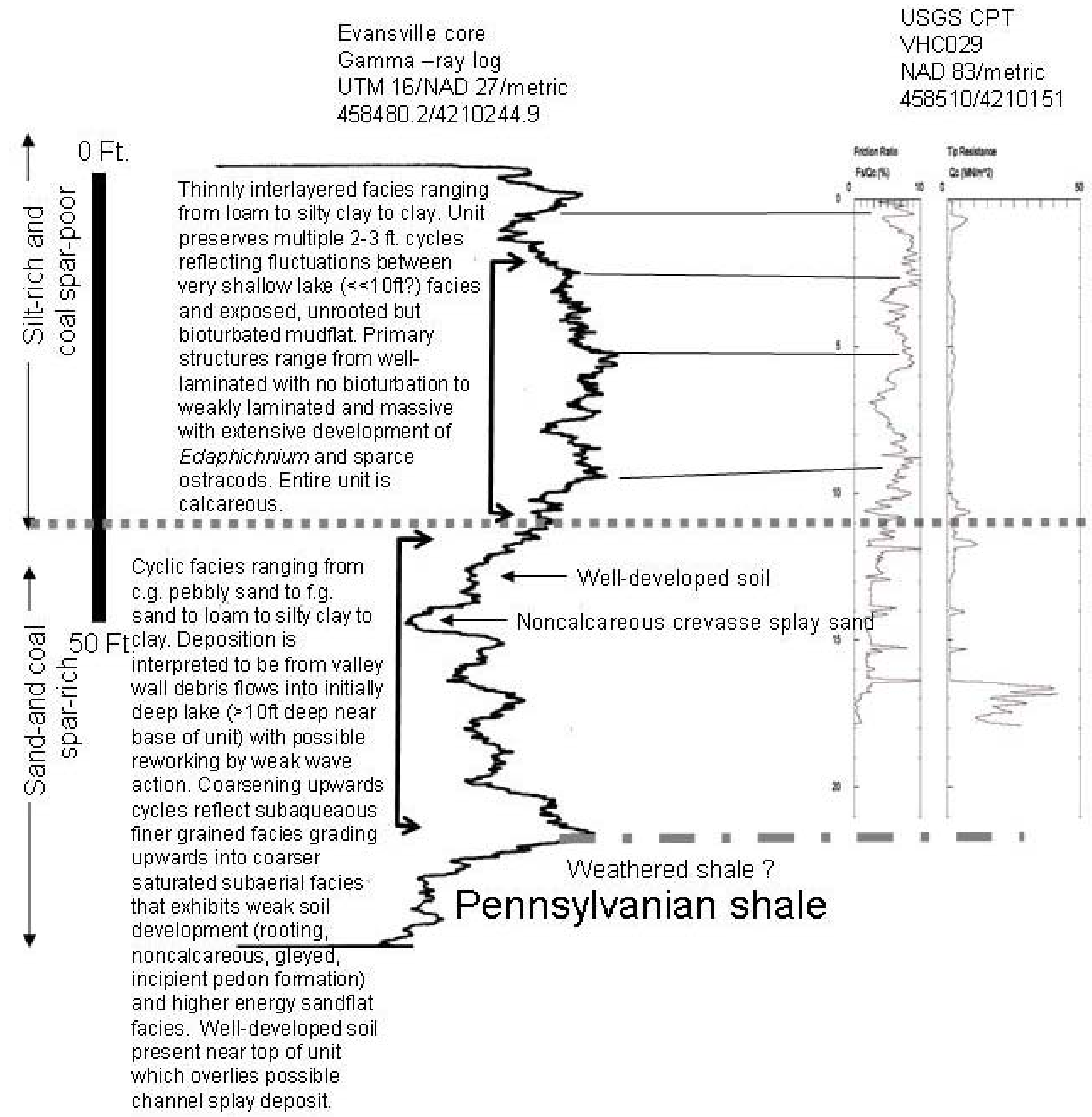

Figure 10. Comparison of IGS core hole gamma-ray log (left) and the USGS CPT log (right). A brief description of facies encountered in the core hole and a preliminary interpretation of those facies is also provided. The dotted line delineates the boundary between the upper and lower Quaternary units discussed in the text. The dashed line above the weathered shale marks the Pennsylvanian-Quaternary unconformity.

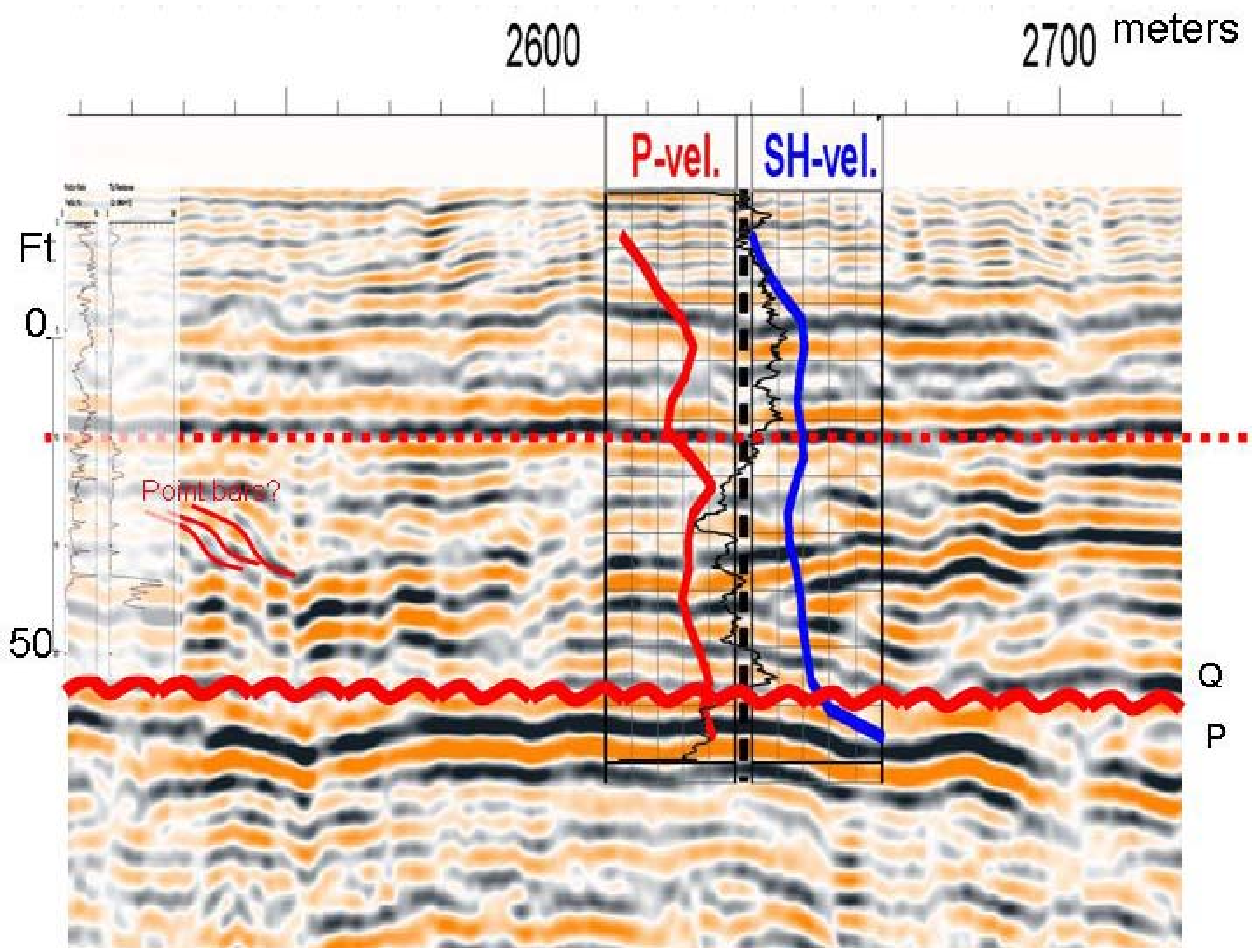

Figure 11. Image shows a segment of the County Line HRSRD with the P- and shear-wave velocity profiles superimposed (detailed shear wave profile in figure 12). Also included are the IGS gamma-log and nearby USGS CPT profiles. All profiles are hung on elevation and in correlative positions. The red dotted line corresponds to the boundary between the upper and lower Quaternary units discussed in the text. The Pennsylvanian-Quaternary unconformity is shown with a red wavy line.

Depth (m)	S-Vel. (m/s)
1.9812	94
3.2004	123
4.4196	170
5.6388	231
6.858	237
8.0772	226
9.2964	219
10.5156	231
11.7348	235
12.954	211
14.1732	193
15.3924	197
16.6116	217
17.8308	227
19.05	233
20.2692	245
21.4884	258
22.7076	308
23.9268	453

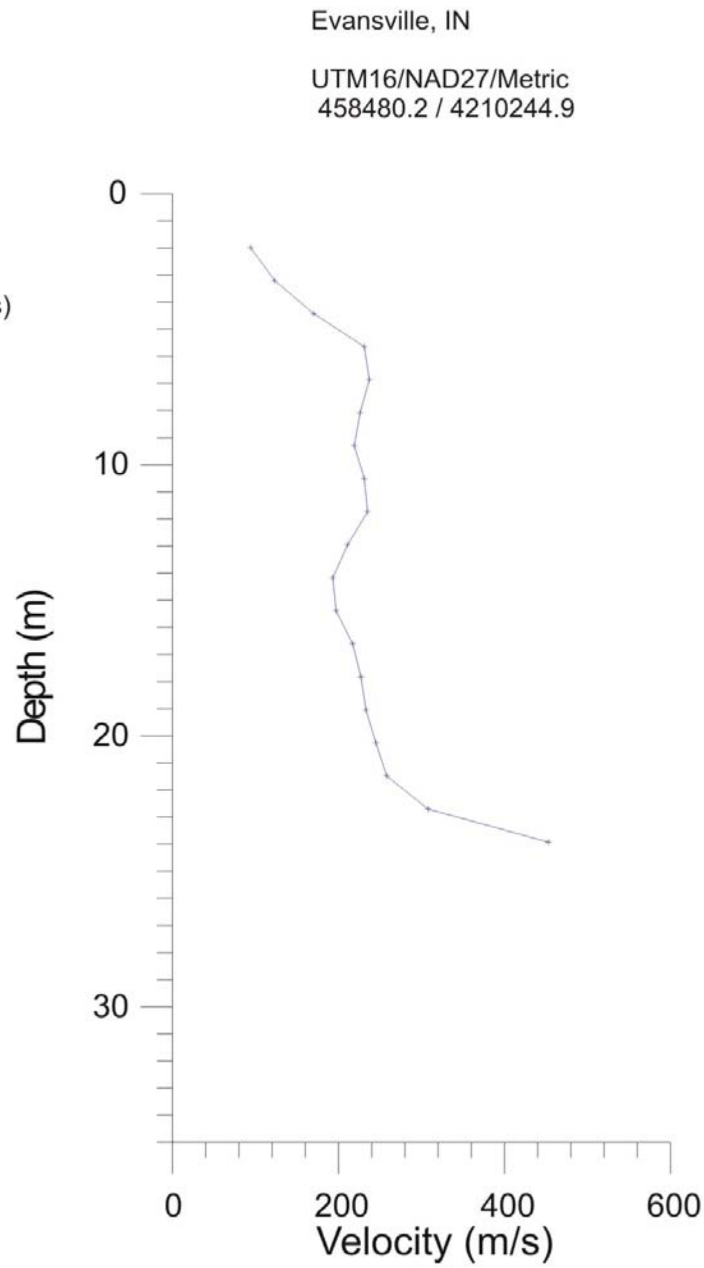

Figure 12. Shear wave profile of borehole shown in figures 8 & 11.

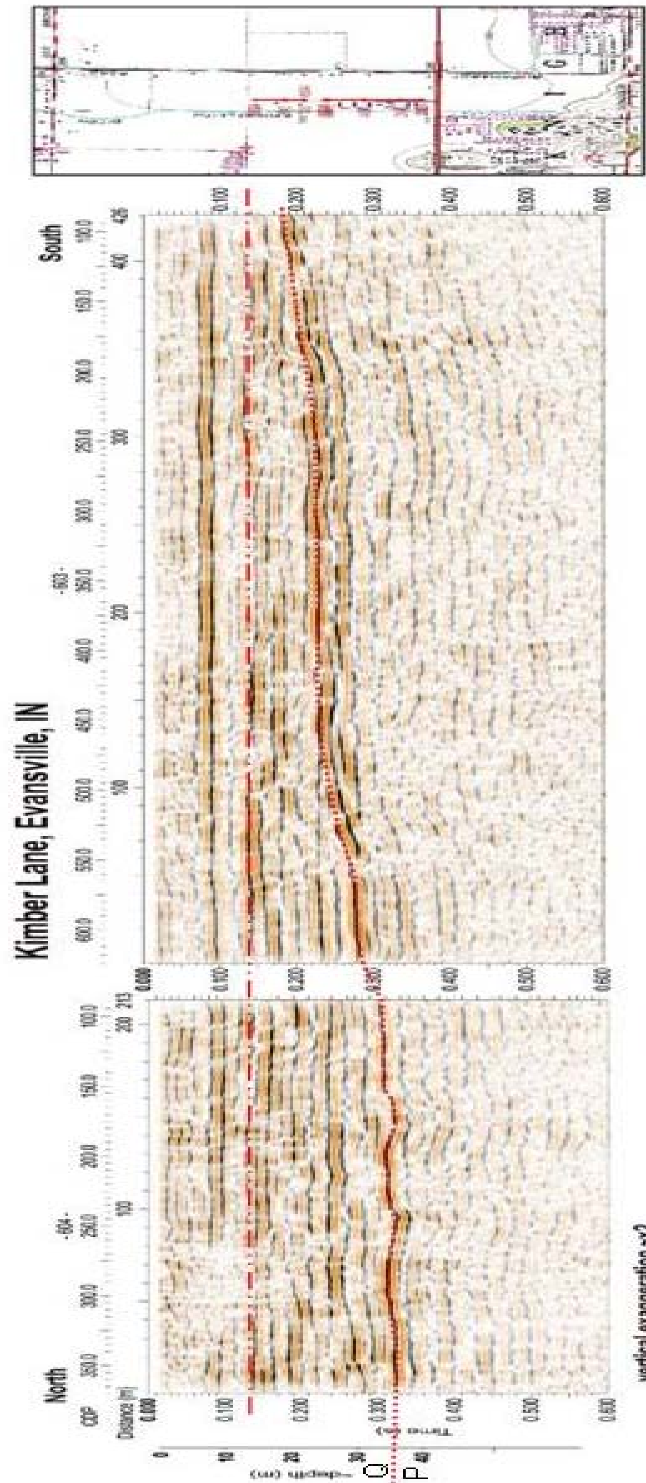

Figure 13. Kimber Lane HRSRD profile showing the Pennsylvanian-Quaternary unconformity (dotted line) and the boundary between the upper and lower Quaternary units (dashed line) discussed in the text. Note the seismic reflectors that appear to onlap the P-Q unconformity in the lower Quaternary unit.

Cooperation with USGS Seismic Cone Penetrometer Testing

During the late 2003 and 2004 the state geological surveys assisted with siting and utility clearance for Seismic Cone Penetrometer Testing of the USGS truck from the Menlo Park office. Fifty-one sites were tested in the Evansville area, three areas in the Vincennes, Indiana area of large paleoliquefaction features and one in Griffin, Indiana near a paleoliquefaction feature from a coarse sand – gravel source (figure 14 & 15).

Figure 14. Paleoliquefaction features in Griffin, Indiana sand and gravel pit. Features color is enhanced for visibility.

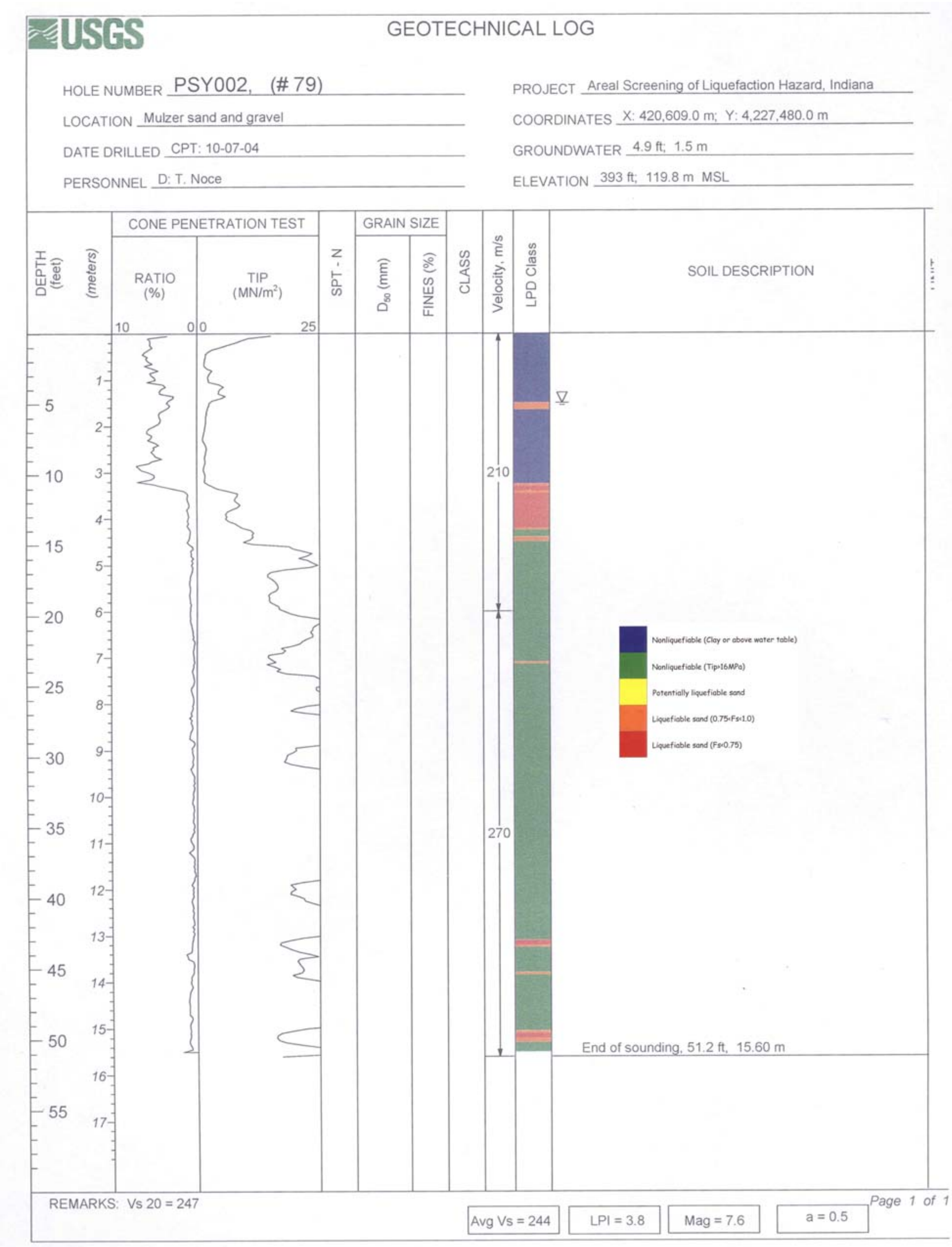

Figure 15. USGS CPT, liquefaction potential classification and shear wave velocities Griffin Quarry, Indiana (location is Griffin site on figure 4).

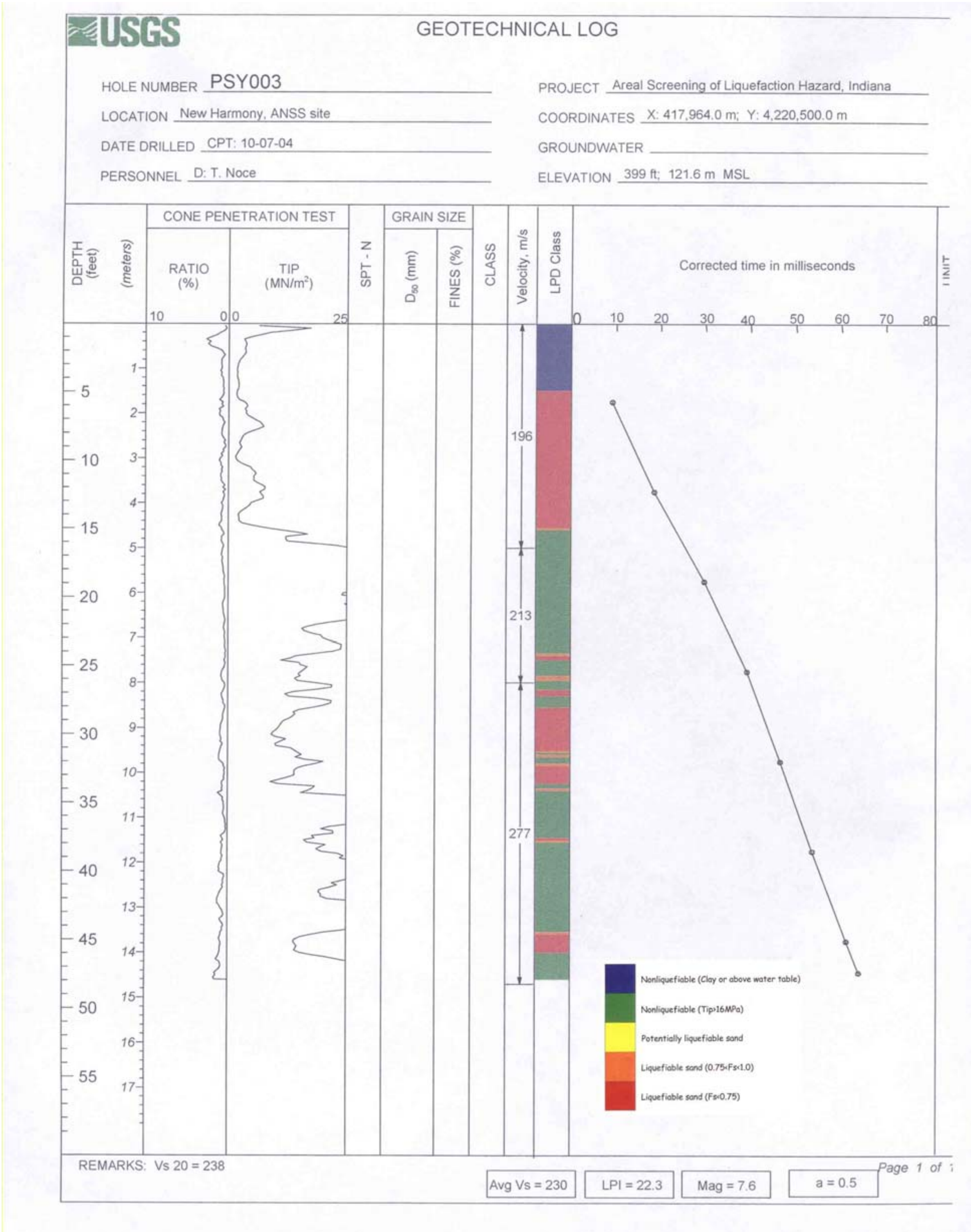

Figure 16. USGS CPT, liquefaction potential classification and shear wave velocities New Harmony, Indiana (location is ANSS site on figure 4).

Kentucky Geological Survey

Introduction

As a part of the Tri-State (Evansville) Urban Hazard Mapping project of Indiana, Kentucky and Illinois, 15 SH-wave seismic refraction profiles with a single and multiple spreads were collected to determine shear-wave velocities of the unlithified soils and bedrock in the Henderson-Owensboro area of Kentucky (figure 17). The SH-wave refraction profiling was also coordinated with the surficial geologic mapping project in the area performed by the Kentucky Geological Survey.

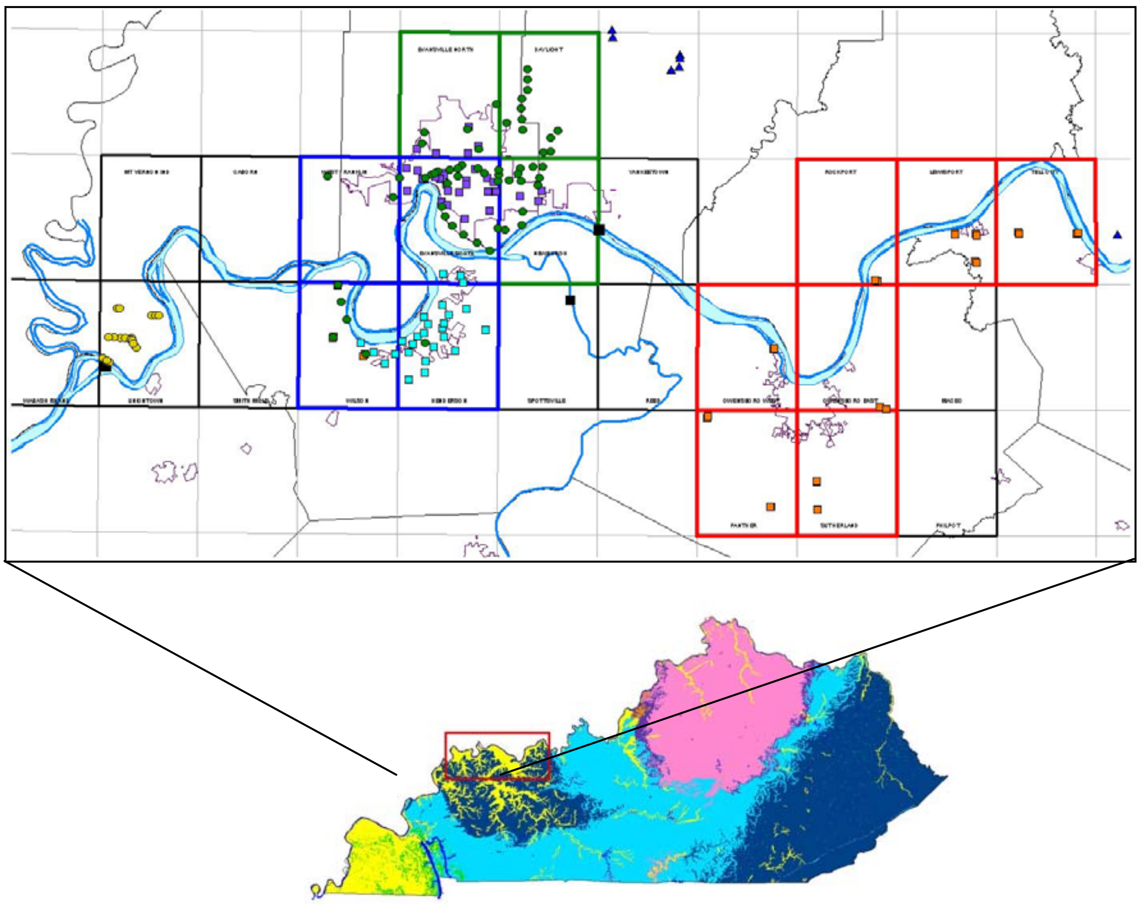

Figure 17. Map showing locations of the Shear-wave measurements (red rectangle).

Field Methods

The seismic refraction profiling is a seismic “drilling” technique that samples a specific site by a variety of energy-source to receiver offsets. The data set defines the two-way travel to the various subsurface refracting impedance horizons (figure 18). The measured travel time and the known array geometry permit the seismic velocity and depth of each subsurface unit to be calculated.

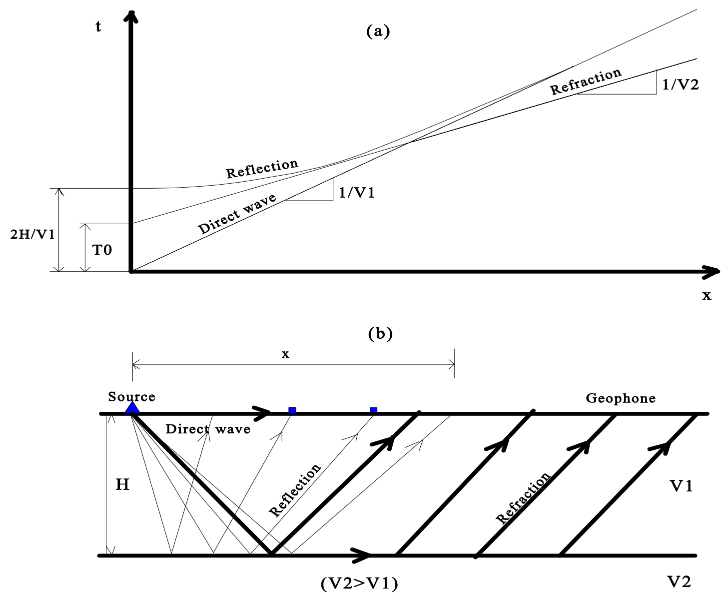

Figure 18. Generalized schematic of the seismic refraction profile for a simple one layer over infinite half space. (a) travel time curve, (b) ray path.

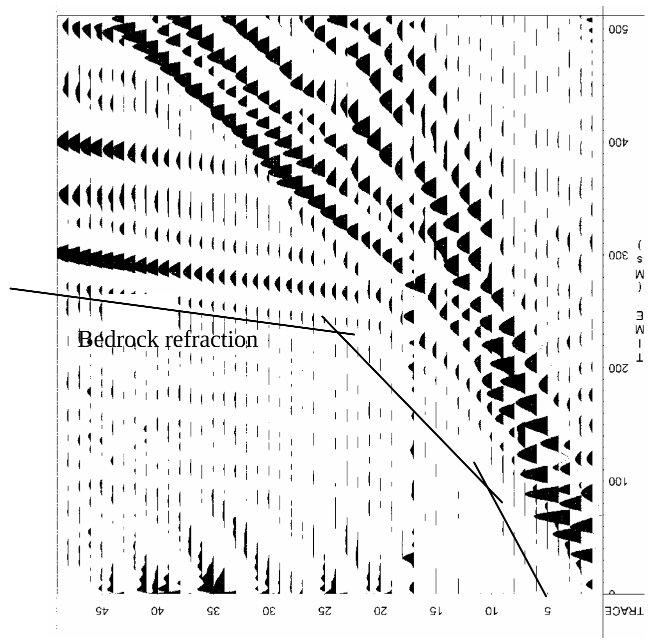

Figure 19. A typical SH-wave refraction profile with two refractors in the Henderson-Owensboro area.

Based on the surficial geologic mapping and site conditions, a single or multiple spreads of SH-wave refraction profile were used to characterize the major soil units and the depth to bedrock.

Figure 19 is a typical SH-wave refraction profile, from which a direct-wave and two refractors were identified, in the Henderson-Owensboro area. The data were collected with an EG and G StrataVisor, 24-bit, 48-channel, floating-point, engineering seismograph. The energy source for SH-wave generation was a 0.3-m section of steel I-beam struck horizontally by a sledgehammer, and the signal receivers are 30-Hz horizontal component geophones from Mark Products. For each shotpoint, signals were stacked two to five times on each direction (reversed) of the energy source. Geophone spacing is 2 meters. The data were processed on a PC using the commercial software package SIP 4.0 by Rimrock Geophysics and VISTA 7.0 by Seismic Image Software.

Results

Figure 20 shows the shear-wave velocity cross-section interpreted from SH-wave refraction data with a single spread at site HO-06. Figure 21 shows the shear-wave velocity cross-section interpreted from SH-wave refraction data with three spreads at site HO-14. It is very interesting that a known fault was "detected" by the SH-wave profiling at the site. The offset on the top of bedrock is about 7 m. Figure 22 shows the shear-wave velocity cross-section interpreted from SH-wave refraction data with 15 spreads at site HO-09. The shear-wave velocity measurements at the center of profile on other sites are listed in table 4.

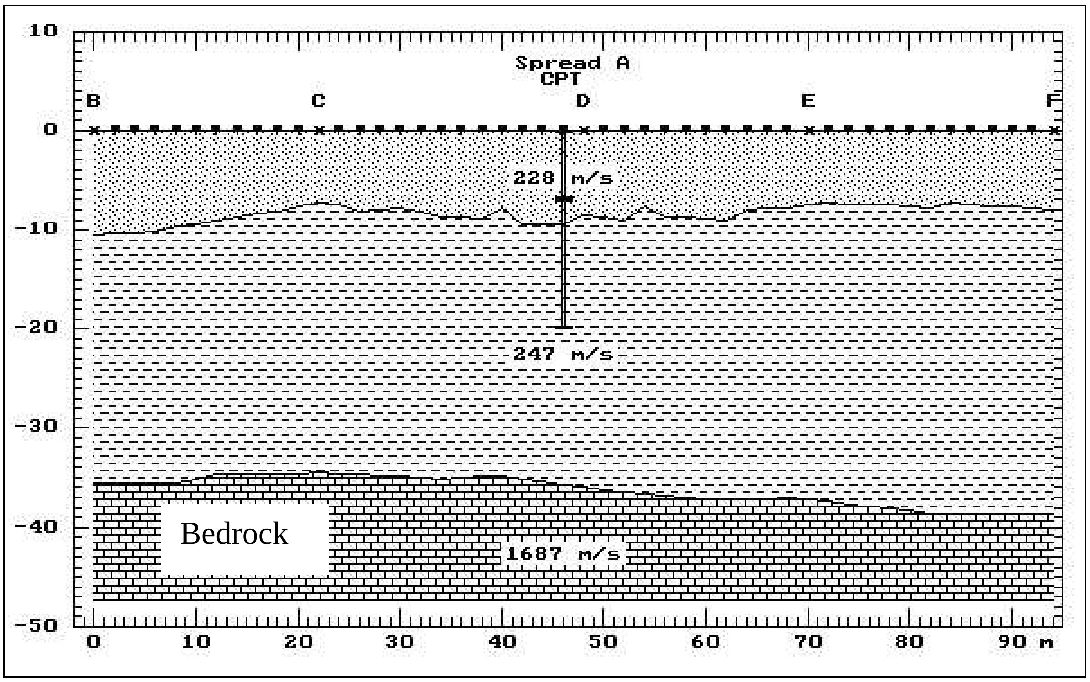

Figure 20. Shear-wave velocity cross-section at Site HO-06.

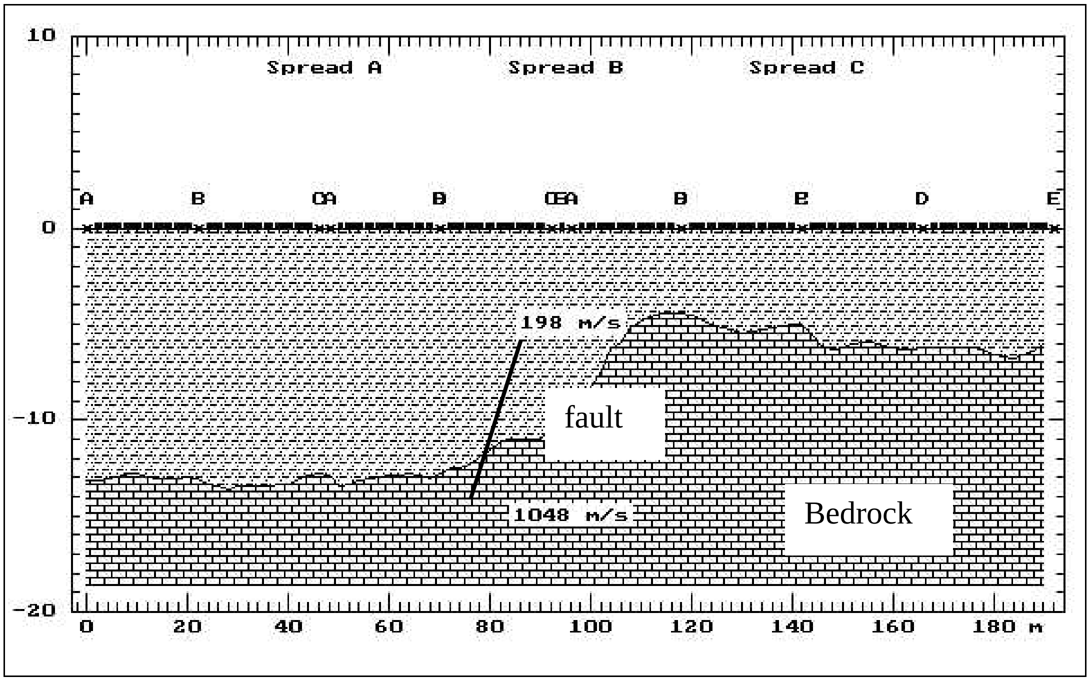

Figure 21. Shear-wave velocity cross-section at Site HO-14.

Table 4. Site location (latitude/longitude) and shear-wave velocities.

Site	Latitude	Longitude	Layer 1		Layer 2		Layer 3		Bedrock	
			Vs	Thick	Vs	Thick	Vs	Thick	Vs	Thick
HO-01	37.878N	87.026W	238	15	390	22			1260	
HO-02	37.898N	86.902W	196	4	243	25			1374	
HO-03	37.925N	86.901W	324	44					1463	
HO-04	37.743N	87.238W	172	3	214	34			1450	
HO-05	37.803N	87.668W	167	12					1484	
HO-06	37.820N	87.707W	228	10	247	26			1687	
HO-07	37.872N	87.702W	191	10	206	18			1163	
HO-08	37.811N	87.155W	301	10					1178	
HO-09	37.752N	87.018W	105	3	180	12			1250	
HO-10	37.651N	87.100W	116	3	197	15			1541	
HO-11	37.654N	87.158W	145	8					1166	
HO-12	37.679N	87.101W	125	2	215	14			1241	
HO-13	37.925N	86.928W	304	32					948	
HO-14	37.926N	86.848W	198	10					1048	
HO-15	37.956N	86.774W	175	2	220	14			514*	

Unit: Vs – m/s, Thick – m.

* low shear-wave velocity (probably shale)

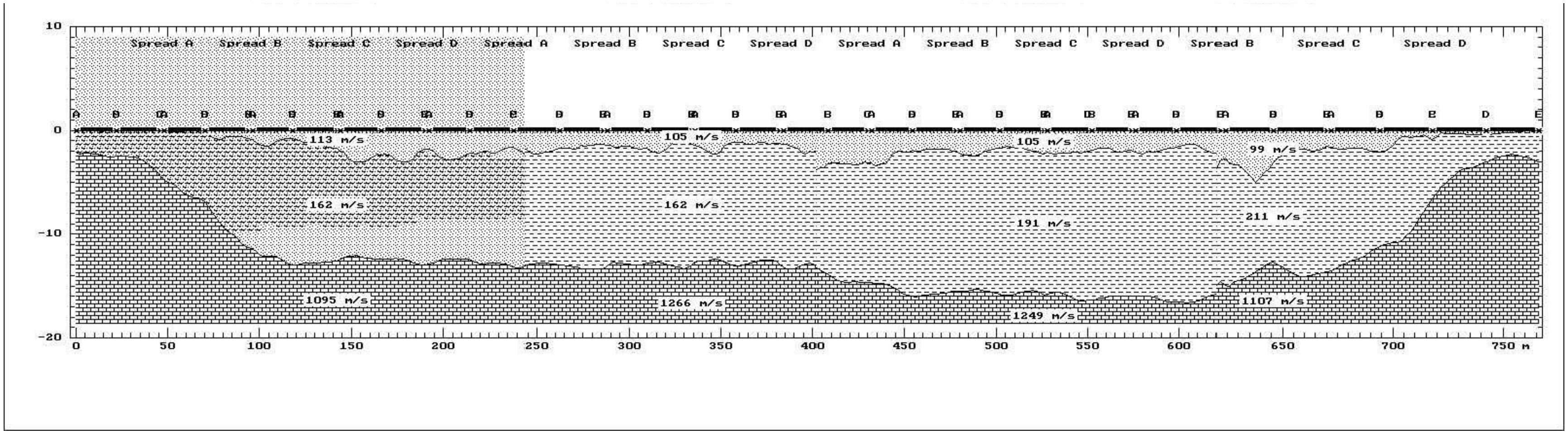

Figure 22. Shear-wave velocity cross-section at Site HO-09.

Missouri Geologic Survey

The chief NEHRP related activity completed in Missouri was a seismic soil amplification map for a four quadrangle area centered on Poplar Bluff in southeastern Missouri (Hoffman, 2004). This map used existing geologic and surficial material mapping and collected new shear-wave data. Of these shear wave data sets, 18 sites in alluvial settings were tested with the generous assistance of the Missouri Department of Transportation using a seismic cone penetrometer. The seismic cone penetrometer could not be used in upland settings with very stony, bedrock residuum, soils. In these settings additional data were collected using surface geophysical techniques. One collaborative effort included the assistance from the Kentucky Geological Survey/University of Kentucky to collect shear wave data using a surface technique that employs shear waves at 10 sites. The University of Missouri at Rolla (UMR) was contracted to complete a second surface geophysical technique, a multi-channel analysis of surface waves (MASW) to derive 2-d shear-wave velocity profiles at 40 sites. Shear wave data collection tests using surface geophysical techniques can be used in any geological setting regardless of surficial material types. In all, the Poplar Bluff project had 58 separate and new shear wave tests at 40 sites.

A second campaign led to the collection of shear wave data at 20 additional sites in 10 eastern Missouri counties, including 11 sites in the St. Louis metropolitan area (figure 23). In this effort UMR was again contracted to conduct MASW geophysical surveys to develop 2-dimensional shear wave profiles. The sites in the St. Louis area will be an important addition to the data needed to evaluate seismic hazards for the proposed St. Louis Urban Hazard Mapping Project.

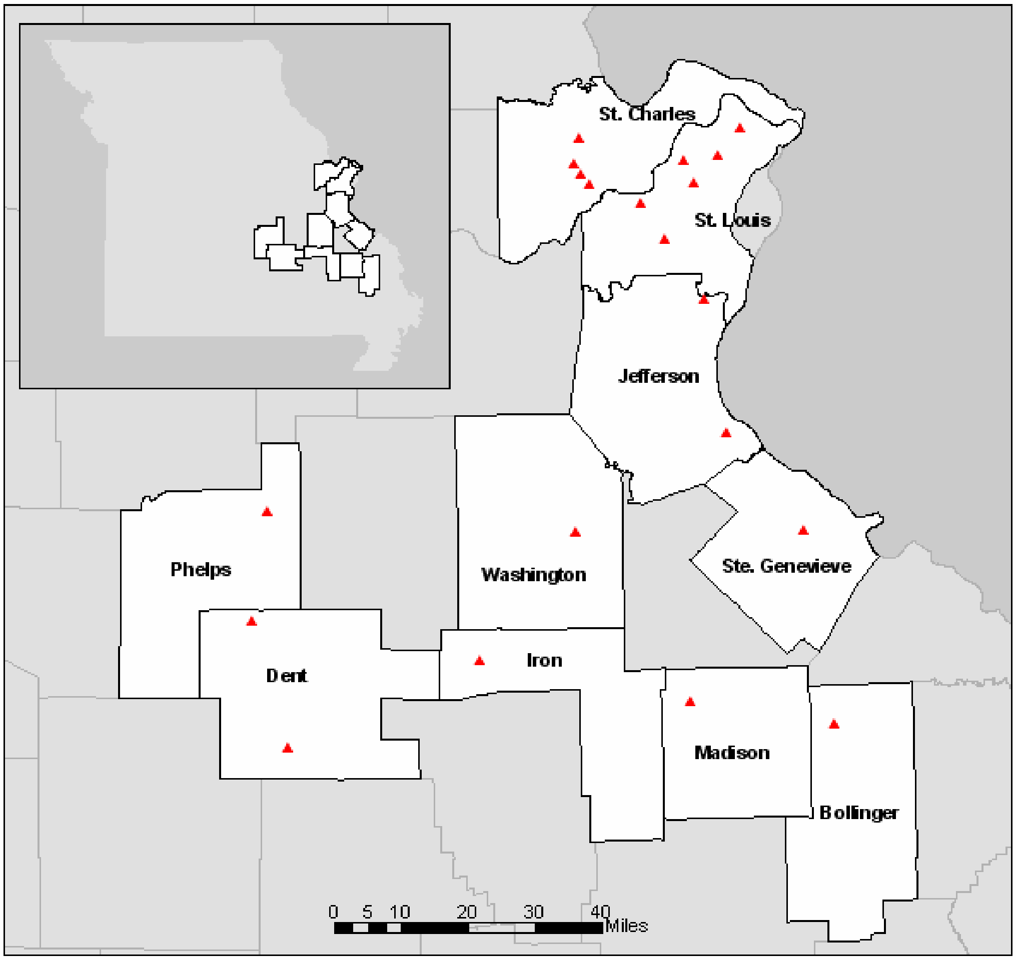

Figure 23. Shear wave data collected at 20 sites in 10 eastern Missouri counties, including 11 sites in the St. Louis metropolitan area using the MASW geophysical survey used by the University of Missouri-Rolla.

Summary

The Central U.S. Earthquake Consortium (CUSEC) State Geologists are gathering geological information to first produce geologic maps of the materials resting on the bedrock at a scale of 1:24,000 or 1 inch = 2,000 feet in the cooperative earthquake hazard mapping areas of St. Louis Urban Hazard Mapping and the Tri-State (Evansville) Urban Hazard Mapping area of Indiana, Kentucky and Illinois. The geologic maps along with measurements of the soil's properties are used to classify the various soils as to how much they will amplify earthquake ground motions. The amplification maps can be used in the Federal Emergency Management Agency's earthquake loss estimation program (HAZUS) to better estimate the amount of damages a community may expect from various earthquakes. This work entails gathering all existing borehole information, "drilling" new holes for stratigraphy, measuring shear wave velocity leading to the production of new maps of the "soils" and their thickness. The average shear wave velocity is calculated for the total column of "soil" and used to produce a map classifying the soils as to how much they will amplify earthquake ground motions.

The data is mostly being assembled in paper copy until there is a consensus on a form of a database for the two urban hazard mapping areas and support is secured for extensive work on such a database.

References

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